NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3417

MEASUREMENTS OF FREE-SPACE OSCILLATING PRESSURES NEAR A PROPELLER AT FLIGHT MACH NUMBERS TO 0.72

By Arthur W. Vogeley and Max C. Kurbjun

Langley Aeronautical Laboratory
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SUMMARY

In the course of a short flight program initiated to check the Garrick-Watkins theory (NACA TN 3018), a series of measurements at three stations were made of the oscillating pressures near the propeller at flight Mach numbers up to 0.72. These measurements were made at a single radial station and at three axial positions (ahead of, in the plane of, and behind the propeller disk). Despite the limited scope of the tests, agreement with the Garrick-Watkins theory was obtained to the extent that:

(a) The oscillating pressures near the propeller tend to decrease with increase in flight Mach number up to a Mach number of approximately 0.5 and to increase rather rapidly at higher Mach numbers.

(b) The sound-pressure levels of the higher harmonics of the propeller noise increase at a higher rate with increase in flight Mach number than the lower propeller harmonics.

In contradiction to the results found for the propeller studied in NACA TN 3018, the oscillating pressures in the plane and ahead of the propeller were found to be higher than those immediately behind the propeller. Factors such as variation in torque and thrust distribution, which could not be investigated in the present test, may account for this contradiction.

INTRODUCTION

The effect of the near-field noise generated by propellers in flight is of continuously increasing concern to the aviation industry. With regard to air transportation, the oscillating pressures in the form of noise directly affect passenger comfort and the field of public relations. For the airplane structural engineer, these oscillating pressures are creating serious fatigue problems. Evidence is also accumulating that these oscillating pressures have important effects on the increasingly complex electronic and mechanical equipment in the airplane. The severity of the problems increases with the continual trend toward higher powers and higher flight speeds. Detailed knowledge of the pressure fields about propellers and jets is necessary for design and also, it is hoped, will eventually indicate a means of reducing the oscillating pressures.

In the field of propeller-generated pressures, both the theoretical and experimental backgrounds are rather extensive. The Gutin theory (ref. 1) for the far-field pressures is well known. This theory has been extended in reference 2 to predict the pressures in the near field. Both references 1 and 2 deal strictly with stationary propellers but the results of investigations under static conditions have been applied with some success, as in reference 3, to low flight speeds. Recently, in reference 4, Garrick and Watkins have further extended Gutin's theory to take into account the effect of forward speed. This extended theory includes the stationary propeller and the far-field simplifications as special cases. It has not yet been verified at high forward speeds because of a lack of suitable in-flight measurements.

The primary purpose of the flight test reported herein was to obtain in-flight measurements of propeller noise with which to check, if possible, the theory of reference 4, although the maximum flight Mach number of the available test vehicle was lower than desired.

SYMBOLS

B	number of blades
b	blade width, in.
c_l	section design lift coefficient
D	propeller diameter, in.
h	blade thickness, in.
J	advance ratio, V/nD
M_o	flight Mach number
M_t	helical tip Mach number, $M_o\sqrt{1 + (\pi/J)^2}$

M_R rotational tip Mach number

N engine speed, rpm

n propeller rotational speed, $0.479 \frac{N}{60}$, rps

P engine-brake horsepower, bh_p

p root mean square of oscillating pressure, lb/sq ft

p_o static pressure, lb/sq ft

R blade radius, in.

r radius to a blade element

T thrust of propeller, lb

t_o free-air temperature, °F

V flight speed, ft/sec

x longitudinal position of microphone, measured positive forward of propeller disk, in.

y radial position of microphone, measured from propeller center, in.

β section blade angle, deg

TEST EQUIPMENT

The airplane available for this investigation was a single-place fighter equipped with a liquid-cooled inline engine. The engine was equipped, as shown in figure 1, with individual jet-ejector exhaust stacks.

The test propeller had a diameter of 11 feet 2 inches and was equipped with four Hamilton Standard 6547A-6 blades. The characteristics of this blade design are given in figure 2 and the blade-tip shape is shown clearly in figure 3. The propeller was driven through a 0.479:1 reduction gear.

The oscillating-pressure pickup used for these tests was a Western Electric condenser-type microphone modified to operate under the rapidly varying static pressures encountered in these tests. A frequency-modulation system was used to transmit the pressure signals to a ground-located magnetic-tape recorder.

The microphone was installed in a boom mounted in the center gunport of the right wing. This location placed the microphone at a radial distance of 7.31 feet from the propeller axis. The boom was constructed in such a manner that the microphone could be shifted forward and backward through a distance of approximately 4 feet. Figures 1 and 3 show the microphone boom installation.

Before the start of the flight-test program, the boom was tested in a wind tunnel to check for low background noise over the anticipated flight speed range. It was found that the self-generated overall noise level of the microphone was below 100 decibels.

The response of the system used was flat within ±1 decibel between 80 and 1,000 cycles per second.

Standard NACA recording instruments were used to record dynamic pressure, altitude, free-air temperature, engine speed, and manifold pressure. All instruments were synchronized by a suitable timing system.

TEST PROCEDURE AND DATA REDUCTION

The pilot adjusted engine speed and manifold pressure to the values given by the engine manufacturer's power curves for the desired engine power. The desired airplane Mach number was maintained by adjusting the climbing or diving attitude of the airplane. Holding an essentially steady condition, the pilot turned on the recording instruments and took continuous records of about 10-second duration as the airplane passed through an altitude of 20,000 feet.

Time histories of the flight records were prepared from which the 3-second interval nearest 20,000 feet was selected. This part of the magnetic-tape recording was then analyzed. Conventional methods were used to evaluate the flight conditions and the tape recordings.

All static ground runs and flight tests were made at a fixed radial distance of $y = 0.655D$. Tests were made at three values of longitudinal distance, $x = -0.125D$, 0, and $0.125D$. Static tests and flight tests at Mach numbers from approximately 0.2 to 0.72 were made at an engine speed of approximately 2,700 revolutions per minute with the manifold pressure adjusted to produce approximately 1,000 brake horsepower. Several flight tests at the higher Mach numbers were made at an engine speed between 2,900 and 3,000 revolutions per minute at a power output of approximately 1,500 brake horsepower. In order to measure the oscillating pressures at the several test values of x, it was necessary to make separate flights.

RESULTS AND DISCUSSION

Because it was necessary to make separate flights, it was impossible to repeat the test conditions exactly; the various test conditions are given in table I. In the discussion to follow, the small differences in test conditions are disregarded and the data are compared and examined in only a general manner.

In this report, the root-mean-square oscillating pressures are given in decibels which may be converted, if desired, to pounds per square foot by the following relationship:

$$\text{Decibels} = 20 \log \frac{480p}{0.0002}$$

Effect of Engine Speed at Constant Flight Mach Number and Power

With the microphone in the rearward position, $x = -0.125D$, tests were made at a flight Mach number of approximately 0.5 and at engine speeds varying from approximately 2,500 to 2,950 revolutions per minute. In these runs manifold pressure was adjusted to hold the engine power output constant at approximately 1,050 brake horsepower. The harmonic content of this series of tests is presented in figure 4. In figure 4 and in similar figures to follow, the fundamental blade-passage frequency and the higher harmonics in each run are connected by broken lines for identification. As the engine speed is increased and there is a corresponding increase in propeller tip Mach number (from approximately 0.85 to 0.95), the pressures increase. The increase in pressure of the first harmonic is relatively small whereas the increase becomes greater for the higher harmonics. As shown in figure 4, harmonics higher than the fourth are detected in the frequency spectrum when the engine speed exceeds 2,712 revolutions per minute and corresponds to a propeller tip Mach number of about 0.9. This finding is in agreement with the results of tests on a stationary propeller reported in reference 5.

In order to show the form of the data obtained from the analyzing equipment, a tracing of the frequency spectrum for one of the high-engine-speed tests with the microphone behind the propeller plane is presented in figure 5. The filter band width used for the spectrum shown is 20 cycles per second at the one-half-power level. It is seen that harmonics as high as the seventh are detectable at this condition.

Figure 5 also shows that, with the microphone located behind the propeller plane, the oscillating pressures due to the engine can easily be separated from the oscillating pressures due to the propeller. In and ahead of the propeller plane, the oscillating pressures due to the propeller are higher and also the oscillating pressures due to the engine are attenuated by distance so that, in most of the test conditions, the oscillating pressures due to the engine are masked out by the oscillating pressures due to the propeller. When the engine noise is not masked by the propeller noise, as in figure 5, three frequencies are prominent; these frequencies correspond to the third, sixth, and ninth harmonics of the cylinder firing frequency.

Effect of Flight Mach Number at Constant Engine Speed and Power

Tests at three axial locations of the microphone were made at an engine speed of approximately 2,700 revolutions per minute and power output of approximately 1,000 brake horsepower over a flight Mach number range from about 0.2 to 0.72. Tests under similar engine-operating conditions were also made in the static condition. The frequency analyses of these tests are presented in figure 6.

As shown in figure 6, the trend is for the oscillating pressures to decrease slowly as the flight Mach number increases to approximately 0.5. It is also apparent in this Mach number range that the pressure amplitudes decrease in a systematic manner as the order of the harmonic increases. At a flight Mach number of 0.5, the fifth harmonic first becomes evident. This appearance of the higher harmonics occurs again at a propeller tip Mach number of approximately 0.9. As the flight Mach number is increased above 0.5, the amplitudes of all the harmonics increase rapidly and higher and higher harmonics also become evident in the frequency spectrum. At the highest Mach number tested, up to $M = 0.72$, the amplitudes have increased 6 to 8 decibels; these values correspond to a more than doubling of the oscillating pressures. This result is in quantitative agreement with theoretical calculations presented in reference 6. The theoretical calculations of reference 6 were based on the theory of reference 4.

The frequency spectrum for the in-plane microphone location is shown in figure 7. As shown in figure 6, harmonics as high as the tenth (and sometimes the eleventh) are evident in the frequency spectrum for the in-plane and forward microphone positions. As graphically shown in figures 6 and 7, the steady decrease in amplitude with increase in order of harmonic no longer exists at this highest test Mach number. This result is in qualitative agreement with the predicted variation at sound-pressure level with order of harmonic presented in reference 7. The variations presented in reference 7 were based on the theory of reference 4. As shown in figure 8 and again in agreement with reference 5, this effect is associated with a change in the wave form. In figure 8 tracings of oscilloscope pictures for the tests over the flight Mach number range with the microphone in the forward position are presented. These pictures were obtained by passing the signal from the tape recording through a 500-cycle low-pass filter in order to remove the hash. As the helical tip Mach number exceeds 0.9, the wave form becomes markedly nonsinusoidal and peak-to-peak values become high and thus account for the higher level of the higher harmonics.

In order to permit a more direct evaluation of the variation of pressures with microphone position, the data of figure 6 have been replotted in figures 9 to 13 for various combinations of flight Mach number and engine speed. The general conclusion to be drawn from these figures is that the pressure amplitudes at all test Mach numbers are higher in the plane of the propeller and ahead of the propeller than the pressure amplitudes behind the propeller. The wave forms for the data of figure 13, obtained at the highest test Mach number and engine speed, are presented in figure 14. In this case the tape-recorder signal was passed through a 1,000-cycle low-pass filter. These wave forms are to be compared with the wave form presented in figure 8 for a flight Mach number of 0.72 and a tip Mach number of 1.01. The much steeper pressure gradients and much sharper peaks of figure 14 are attributed to operation of the propeller tips at definitely supersonic speeds.

Correlation with theory of reference 4.- Because of the small number of tests made in this exploratory program, it was not possible to obtain a complete check of the theory of reference 4. The results obtained allow only a few broad generalizations to be made which are as follows:

(1) In agreement with the results of references 4 and 6, the results of these tests, as presented in figure 6, show an initial gradual decrease in the oscillating pressures with a more rapid increase at flight Mach numbers above 0.5. When account is taken of the differences between the flight-test configuration and the configuration examined theoretically in references 4 and 6, the pressure levels and changes in level with Mach number are also in rather satisfactory agreement.

(2) In agreement with reference 4 as shown by a comparison of figure 5 of reference 7 and the present test results, the level of the higher harmonics of the propeller noise was found to increase at a higher rate than the lower harmonics with increase in flight Mach number.

(3) For the propeller studied in reference 4, the oscillating pressures in the plane of the propeller disk and ahead of the disk were found to be lower than those immediately behind the disk. This theoretical

result is in direct opposition to the results found in the present tests, as shown in figures 9 to 13. This contradiction does not, however, invalidate the theory. Rather, it indicates that it may be necessary to investigate the effects of such factors as variations in torque and thrust distribution; these effects could not be determined in the present investigation.

CONCLUSIONS

As part of a brief flight program initiated to check the Garrick-Watkins theory (NACA TN 3018), a short series of measurements were made of the oscillating pressures in the vicinity of a propeller at flight Mach numbers up to 0.72. Measurements were made at a single radial station and at positions ahead of, in the plane of, and behind the propeller disk. The scope of the tests was found to be insufficient to obtain complete verification of the Garrick-Watkins theory for the effect of forward speed on the sound-pressure field around propellers, but it was possible to substantiate the following two phenomena:

(a) The oscillating pressures near the tips of a propeller tend to decrease slowly with increase in flight Mach number up to a Mach number of approximately 0.5 and then to increase rather rapidly at higher Mach numbers.

(b) The sound-pressure levels of the higher harmonics of the propeller noise increase at a higher rate with increase in flight Mach number than do the lower propeller harmonics.

In contradiction to the results found for the propeller studied in NACA TN 3018, the oscillating pressures in the plane and ahead of the propeller were found to be higher than those immediately behind the propeller. Factors such as variations in torque and thrust distributions, which could not be investigated in the present test, may account for this contradiction.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 3, 1955.

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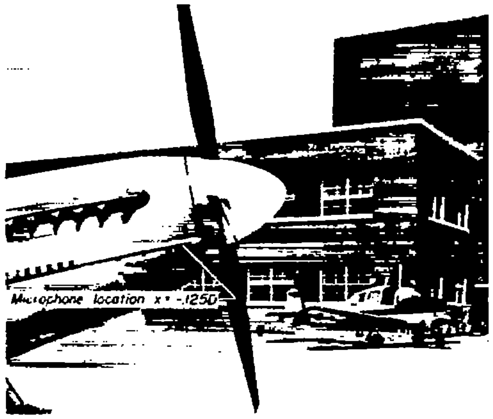
TABLE I

TABULATION OF RESULTS

[y = 0.655D]

Test conditions														Sound-pressure level, db (Reference pressure level, 0.0002 dynes/cm^2)									
														Order of harmonic									
Flight	Test	Figure number	x	T, lb	V, ft/sec	p_o, lb/sq ft	t_o, °F	P, bh_p	N, rpm	M_o	M_R	M_t	Blade passage frequency, cps	1st	2d	3d	4th	5th	6th	7th	8th	9th	10th
Ground	1	6	0.125D	2800	0	----	69	1030	2705	0	0.67	0.67	86.4	131.5	125.5	118.0	111.0	112.0					
	3	6	0	2800	0	----	69	1030	2700	0	.67	.67	86.2	129.5	123.0	118.5	113.0						
	5	6	-.125D	2800	0	----	69	1030	2700	0	.67	.67	86.2	129.0	120.0	119.0	108.0						
1	1	6	-.125D	2160	222	960	5	1030	2697	.21	.72	.75	86.2	125.0	119.0	113.5	109.0						
	2	6	-.125D	1340	359	962	0	1040	2715	.34	.73	.80	86.7	123.5	117.8	112.5	109.5	107.0					
2	3	4	-.125D	915	520	947	-7	1030	2497	.50	.67	.84	79.5	120.5	115.6	109.5	107.5						
	4	4	-.125D	942	513	969	-11	1050	2597	.49	.70	.86	82.9	120.5	116.0	112.0	109.5						
	5	4, 6, 9	-.125D	946	522	961	-5	1060	2712	.49	.72	.88	86.6	121.5	116.5	112.5	108.0						
	7	4	-.125D	960	515	961	-6	1070	2893	.49	.75	.92	92.3	122.5	118.5	116.0	112.5	107.5	104.5				
	8	4, 5, 10	-.125D	963	516	966	-6	1075	2940	.49	.78	.93	94.0	122.0	120.0	118.0	114.5	110.4	106.5				
	9	6, 11	-.125D	756	628	980	-6	1060	2717	.60	.73	.94	86.6	124.5	121.5	118.0	112.5						
	10	6, 12	-.125D	583	757	1075	0	1030	2730	.72	.72	1.02	87.2	135.0	136.5	134.0	131.0	126.0	121.5				
	11	13, 14	-.125D	738	747	1040	-3	1280	2910	.71	.79	1.07	93.0	137.0	139.0	137.0	133.0	126.5					
3	1A	6	0	1830	270	947	9	1048	2710	.25	.71	.76	86.6	129.5	125.0	120.0	115.5						
	2A	6	0	1310	374	943	9	1048	2710	.35	.72	.80	86.6	128.0	124.0	119.5	114.5						
	3	6, 9	0	955	523	951	10	1080	2705	.49	.71	.87	86.4	126.5	123.5	120.5	115.5	111.0					
	4	10	0	1350	524	955	10	1530	2945	.49	.77	.92	94.0	131.0	130.0	128.0	125.0	121.5	117.0	113.0			
	5	6, 11	0	774	633	983	11	1080	2700	.59	.71	.93	86.2	129.0	128.0	126.0	122.5	117.5	112.0	107.5			
	6	6, 7, 12	0	574	767	1000	13	1030	2685	.72	.71	1.01	85.8	138.5	142.0	141.5	138.0	131.0	124.5	128.5	127.0	123.5	121.5
	7	13, 14	0	710	768	1030	18	1270	2910	.72	.76	1.04	92.9	143.5	146.0	142.0	129.5	128.5	129.5	123.0			
4	1	6, 8	.125D	2180	226	952	4	1040	2695	.21	.71	.74	86.0	129.5	124.5	120.0	115.0						
	2	6, 8	.125D	1300	369	945	3	1035	2700	.35	.71	.78	86.2	128	123.0	119.0	113.5						
	3	6, 8, 9	.125D	950	531	968	5	1070	2690	.50	.71	.87	85.8	128.5	125.5	122.0	117.5	114.0					
	4	10	.125D	1360	517	966	5	1530	2945	.49	.78	.92	94.0	131.0	130.5	129.0	126.5	123.0	119.5	114.5			
	5	6, 8, 11	.125D	762	629	985	7	1060	2682	.59	.71	.92	85.6	130.5	129.5	127.0	123.5	119.5	115.0				
	6	6, 8, 12	.125D	606	761	940	6	1080	2665	.72	.71	1.01	85.0	138	139.5	135.1	124.0	126.0	126.5	122.0	120.5	119.0	
	7	13, 14	.125D	890	744	940	5	1530	2920	.70	.77	1.04	93.2	142.5	143.5	133.5	132.5	133.0	121.0	128.0	123.5	124.5	125.0



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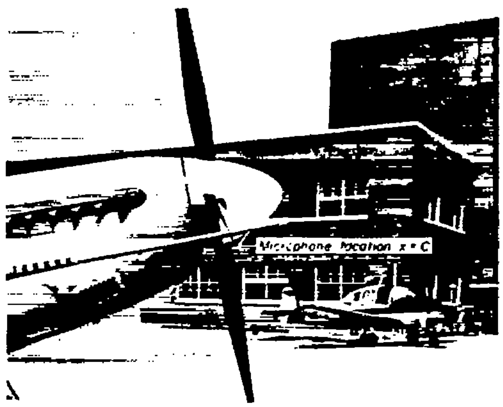

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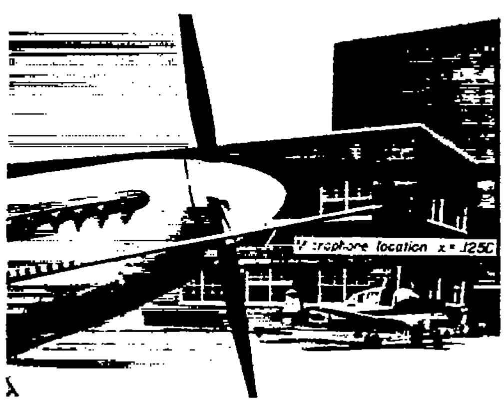

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Figure 1.- Three microphone locations used on the test airplane during the investigation. $y = 0.655D$ for all positions.

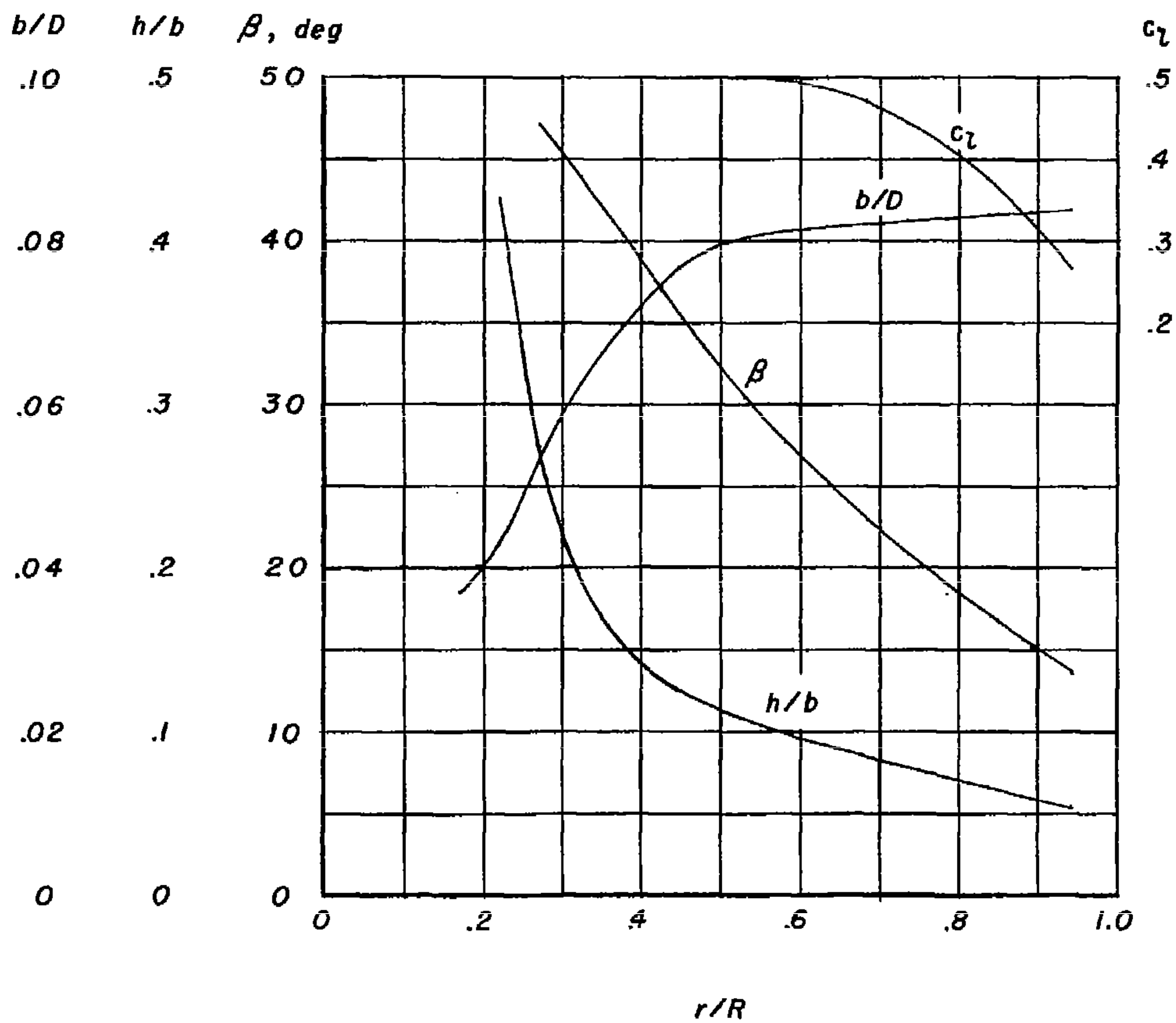

Figure 2.- Characteristics of Hamilton Standard 6547A-6 propeller blade used in the investigation.

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Figure 3.- Front view of microphone installation showing propeller-tip shape.

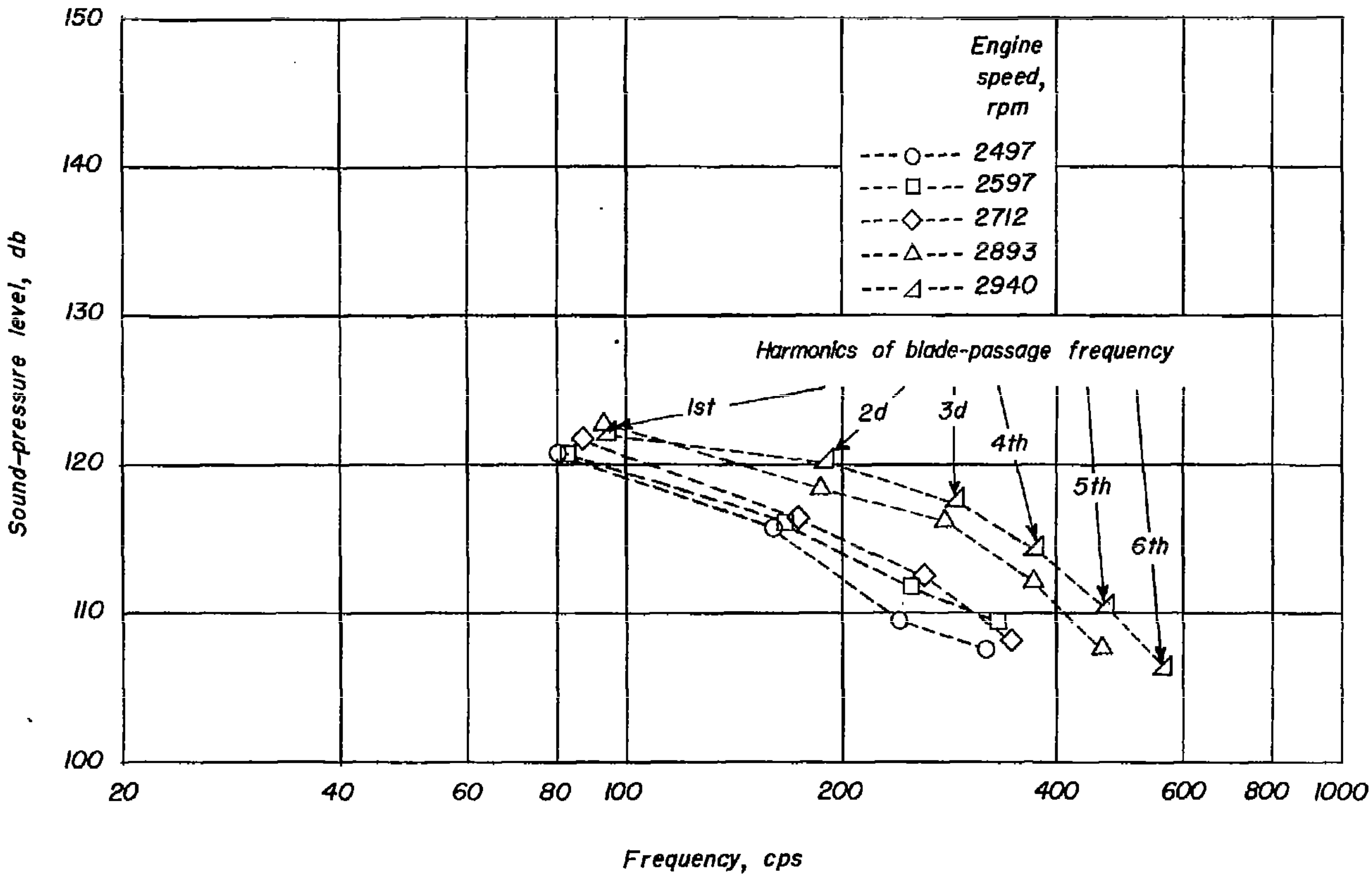

Figure 4.- Variation of sound-pressure levels with engine speed. $M_0 \approx 0.5$; $P \approx 1{,}050$ bhp; microphone location, $x = -0.125D$. Blade-passage harmonics are connected with dashed lines only for identification.

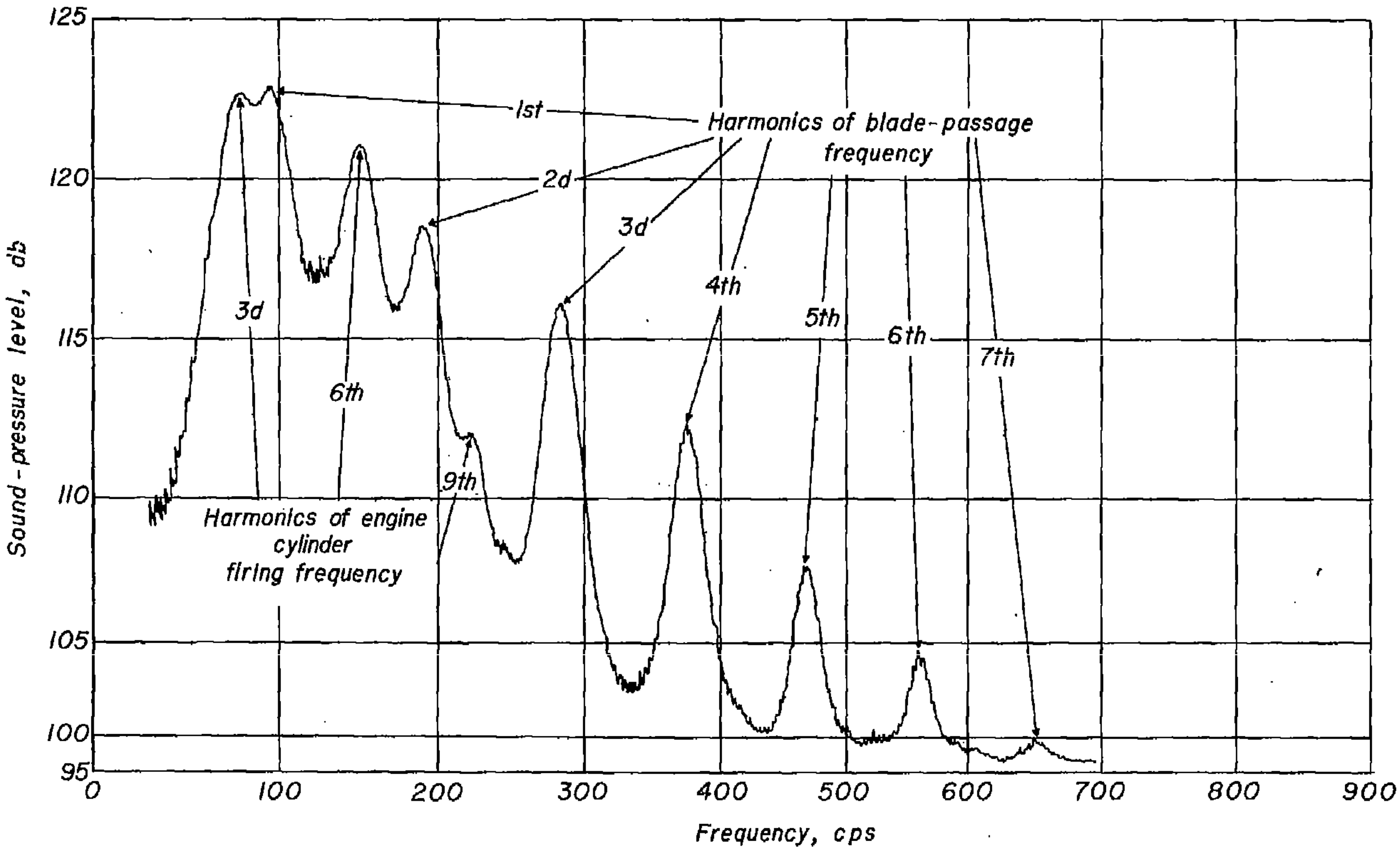

Figure 5.- Frequency spectra for the test condition of flight 2, test 8 (table I).

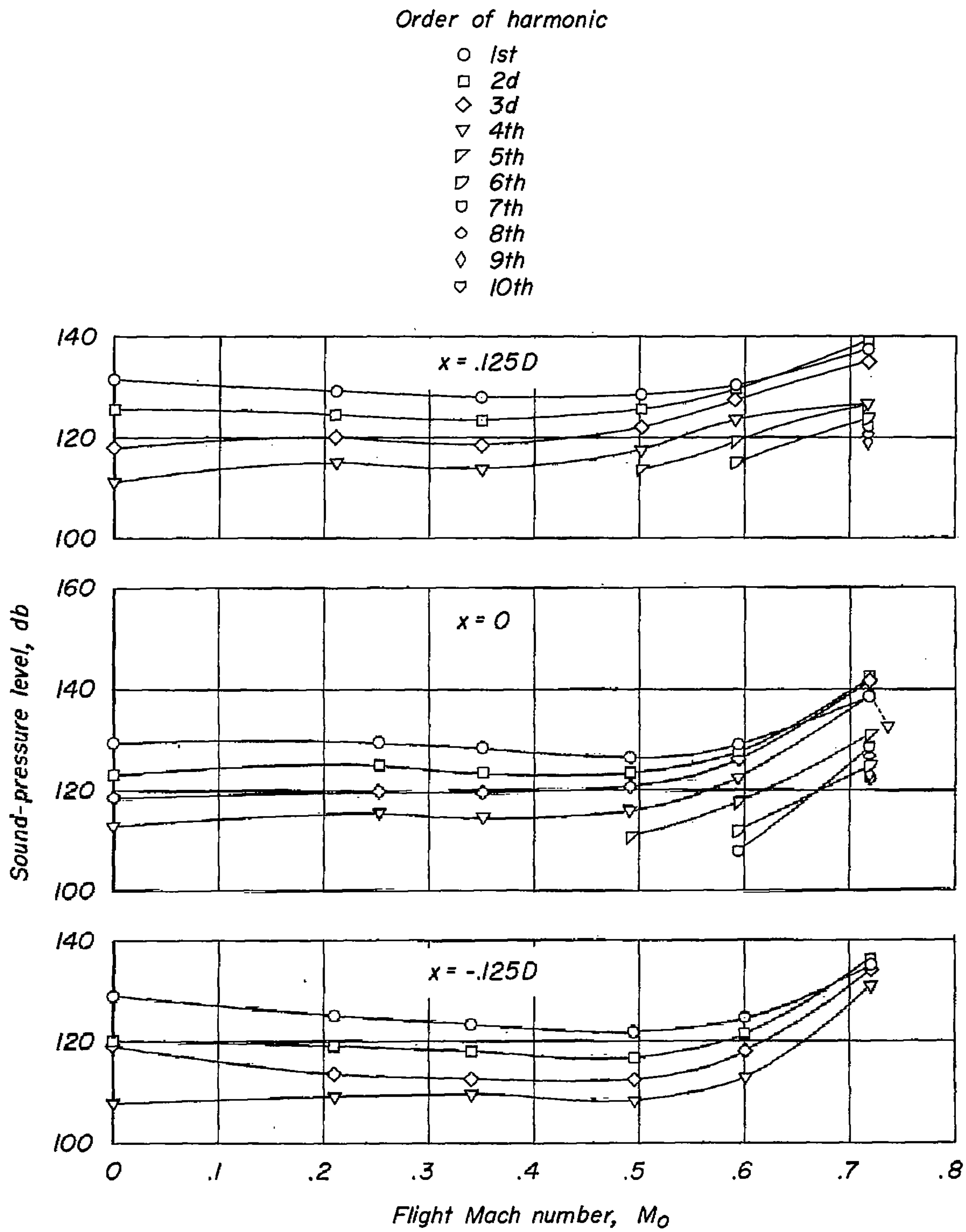

Figure 6.- Variation of propeller noise harmonic content with flight Mach number. $N \approx 2{,}700$ rpm; $P \approx 1{,}000$ bhp; $y = 0.655D$.

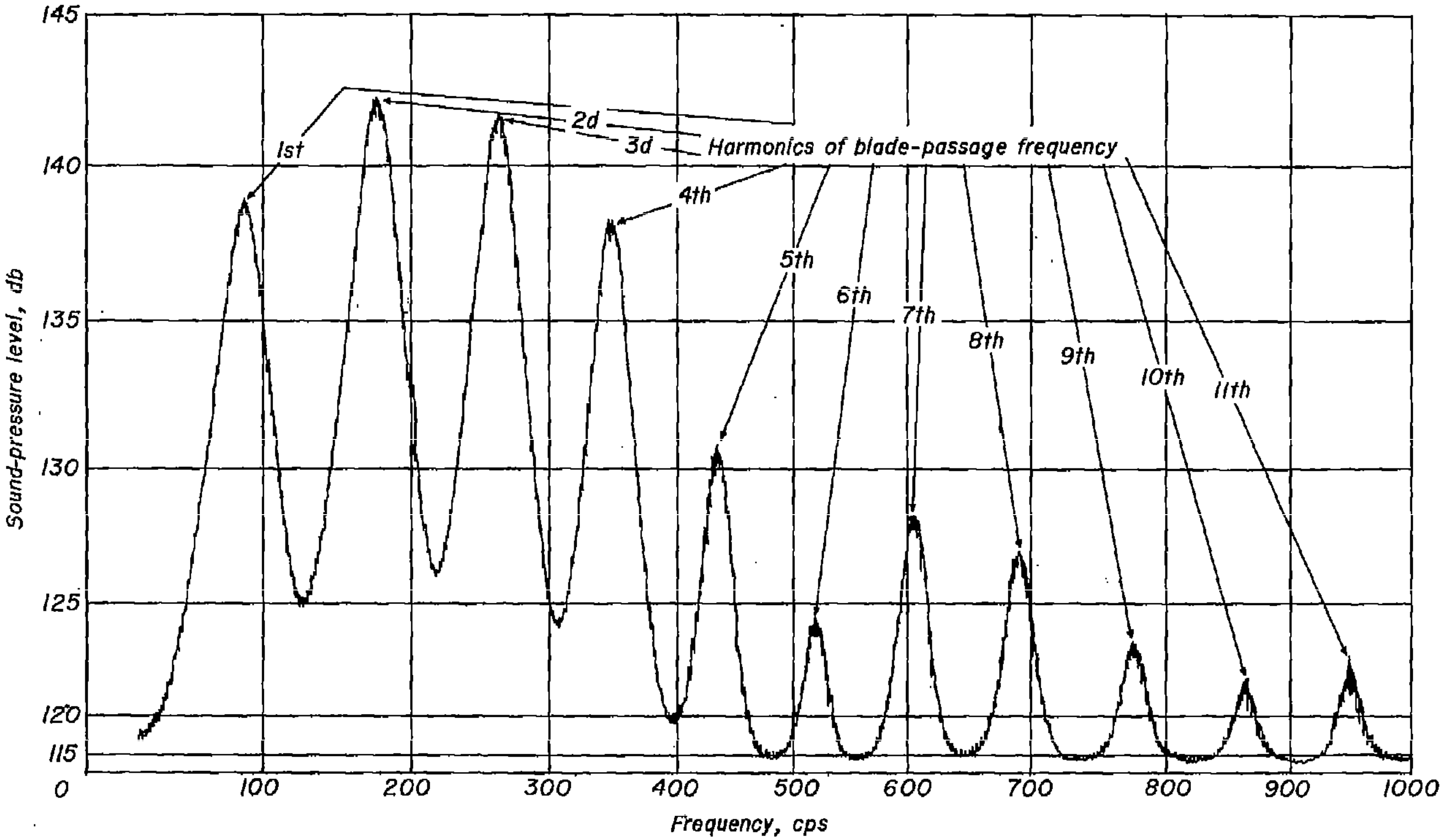

Figure 7.- Frequency spectra for the test condition of flight 3, test 6 (table I).

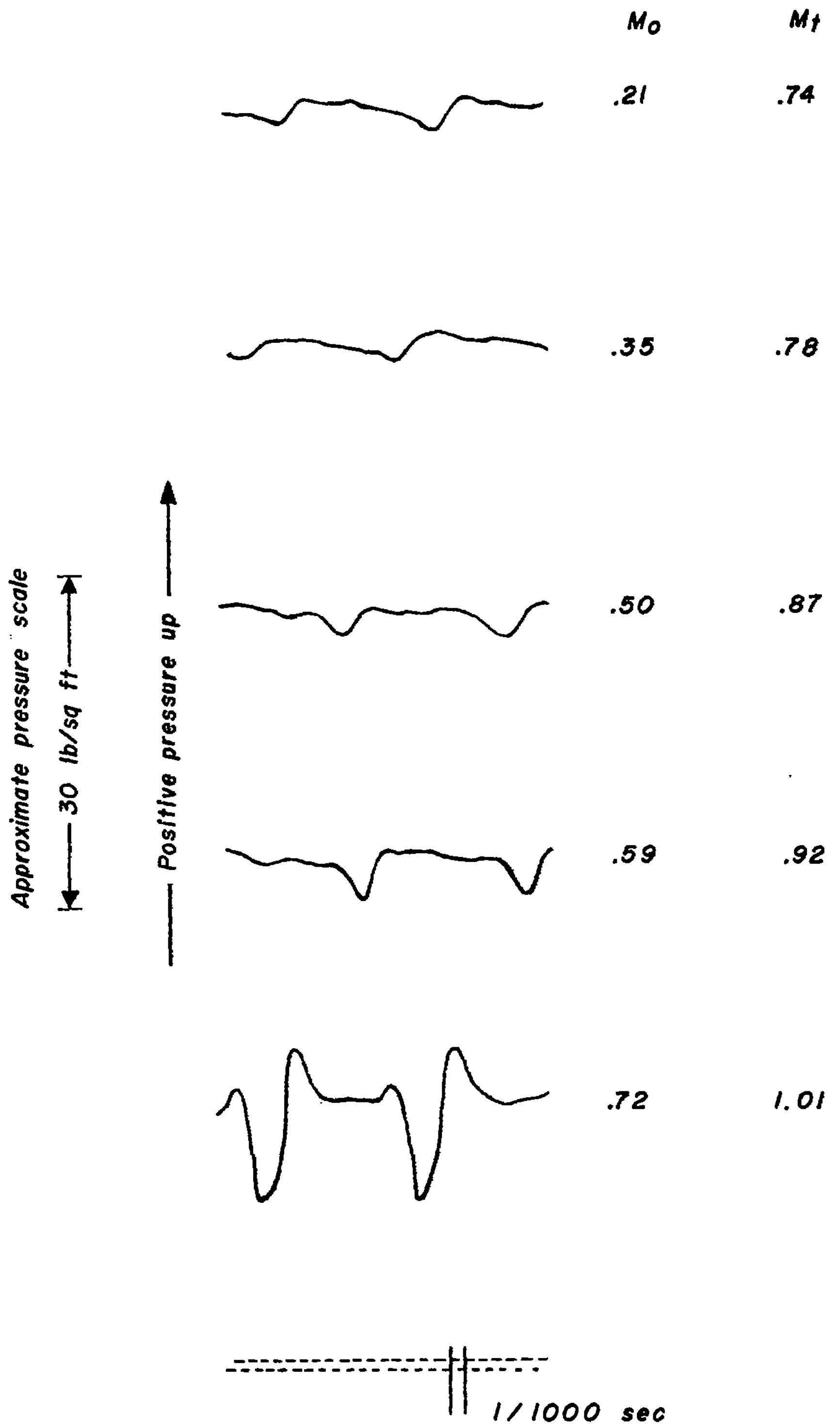

Figure 8.- Variation of wave form of propeller noise with flight Mach number. $N \approx 2{,}700$ rpm; $x = 0.125D$; $y = 0.655D$.

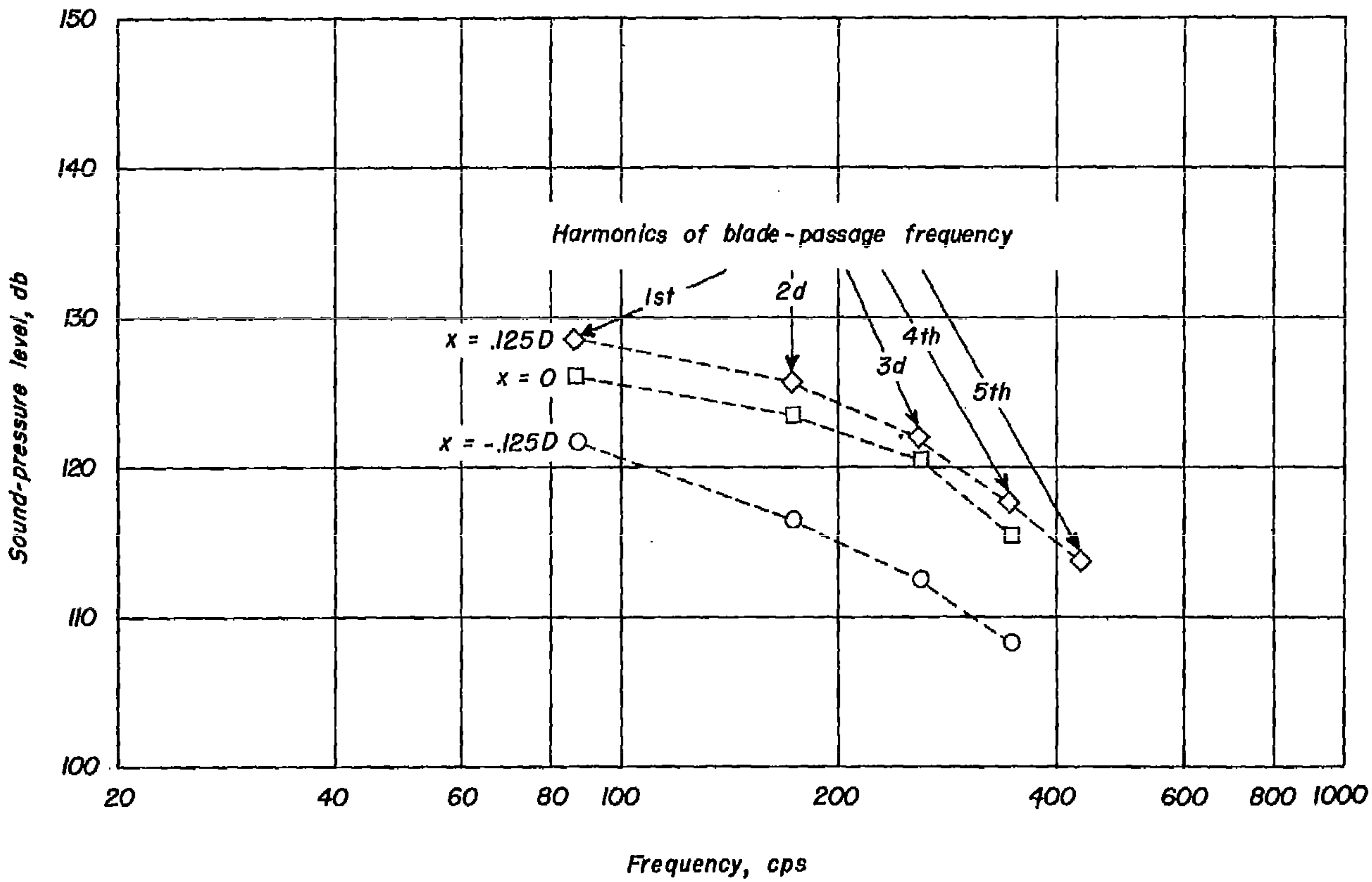

Figure 9.- Variation of sound-pressure levels with axial microphone location. $M_o \approx 0.5$; $N \approx 2{,}700$ rpm; $y = 0.655D$. Blade-passage harmonics are connected with dashed lines only for identification.

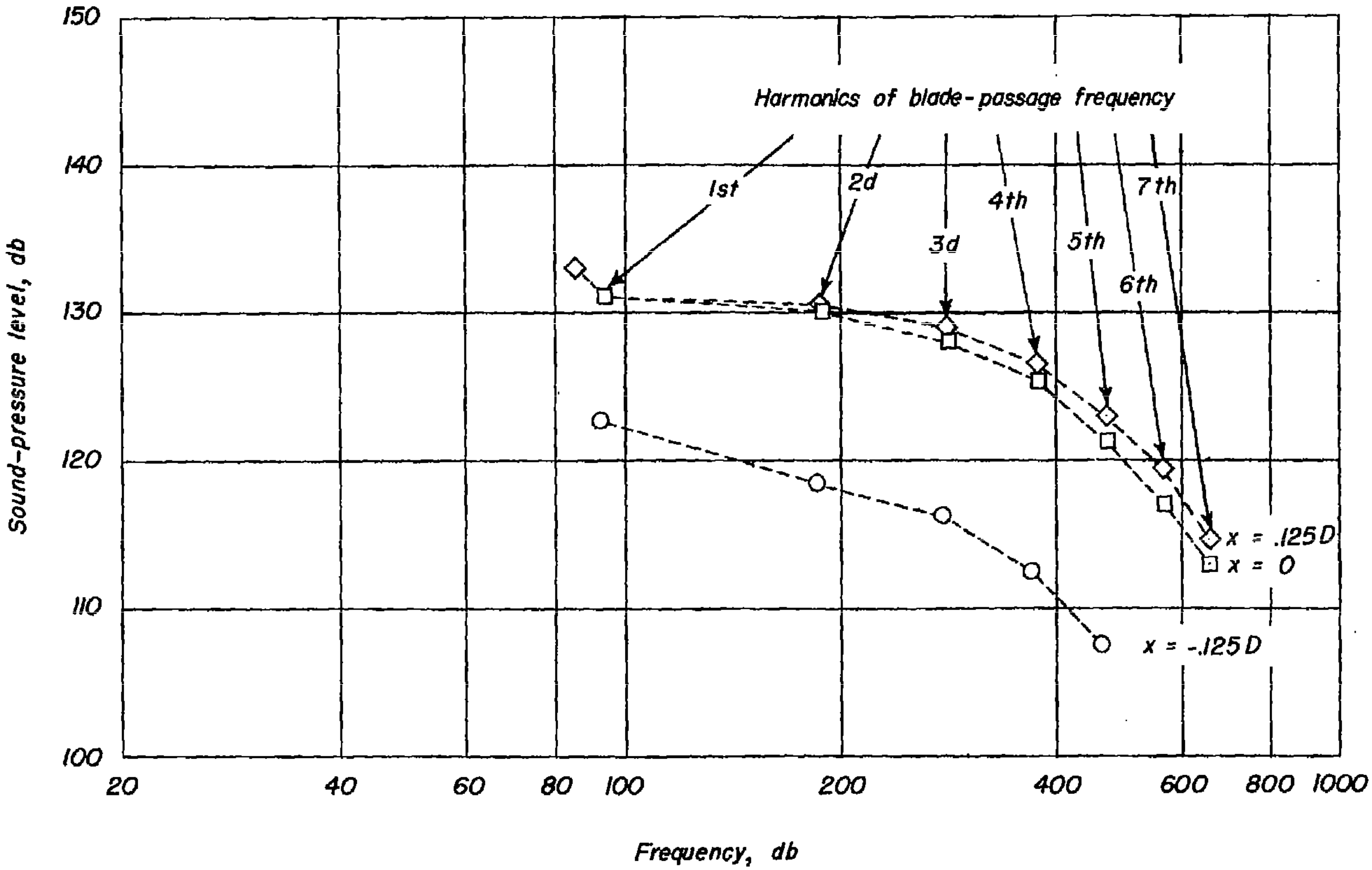

Figure 10.- Variation of sound-pressure levels with axial microphone location. $M_0 \approx 0.5$; $N \approx 2{,}900$ rpm; $y = 0.655D$. Blade-passage harmonics are connected with dashed lines only for identification.

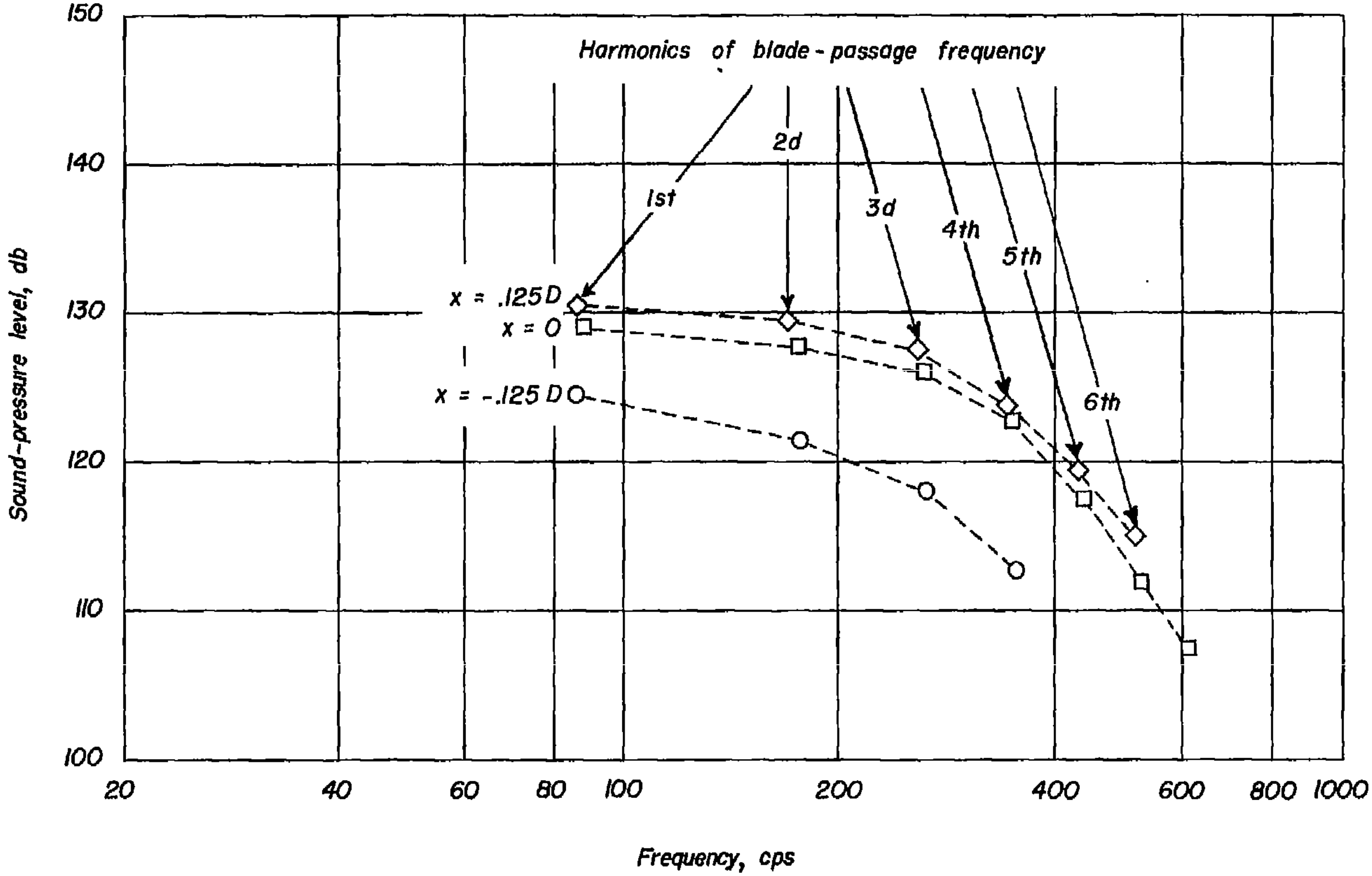

Figure 11.- Variation of sound-pressure levels with axial microphone location. $M_0 \approx 0.6$; $N \approx 2,700$ rpm; $y = 0.655D$. Blade-passage harmonics are connected with dashed lines only for identification.

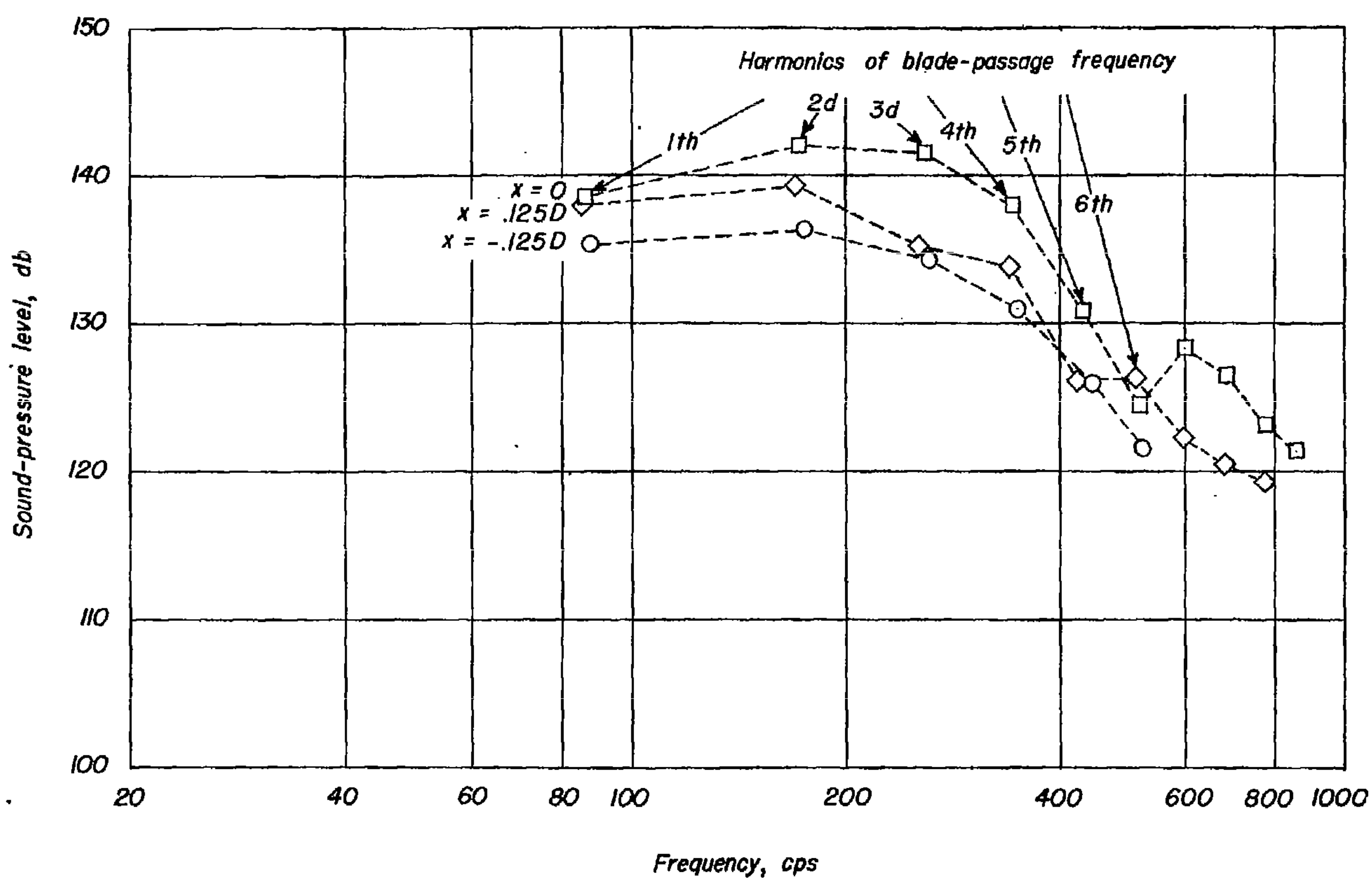

Figure 12.- Variation of sound-pressure levels with axial microphone location. $M_0 \approx 0.72$; $N \approx 2,700$ rpm; $y = 0.655D$. Blade-passage harmonics are connected with dashed lines only for identification.

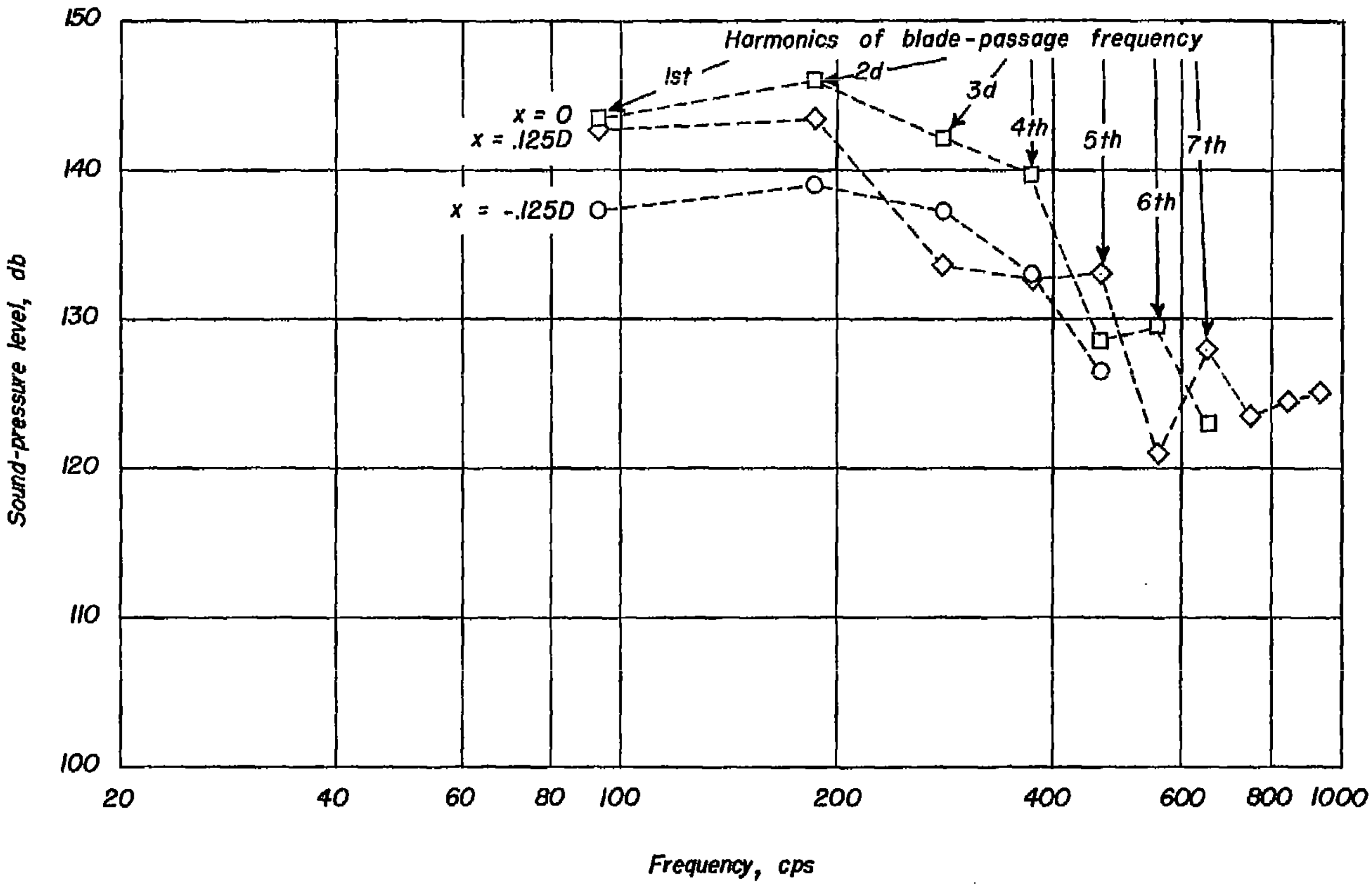

Figure 13.- Variation of sound-pressure levels with axial microphone location. $M_0 \approx 0.71$; $N \approx 2{,}900$ rpm; $y = 0.655D$. Blade-passage harmonics are connected with dashed lines only for identification.

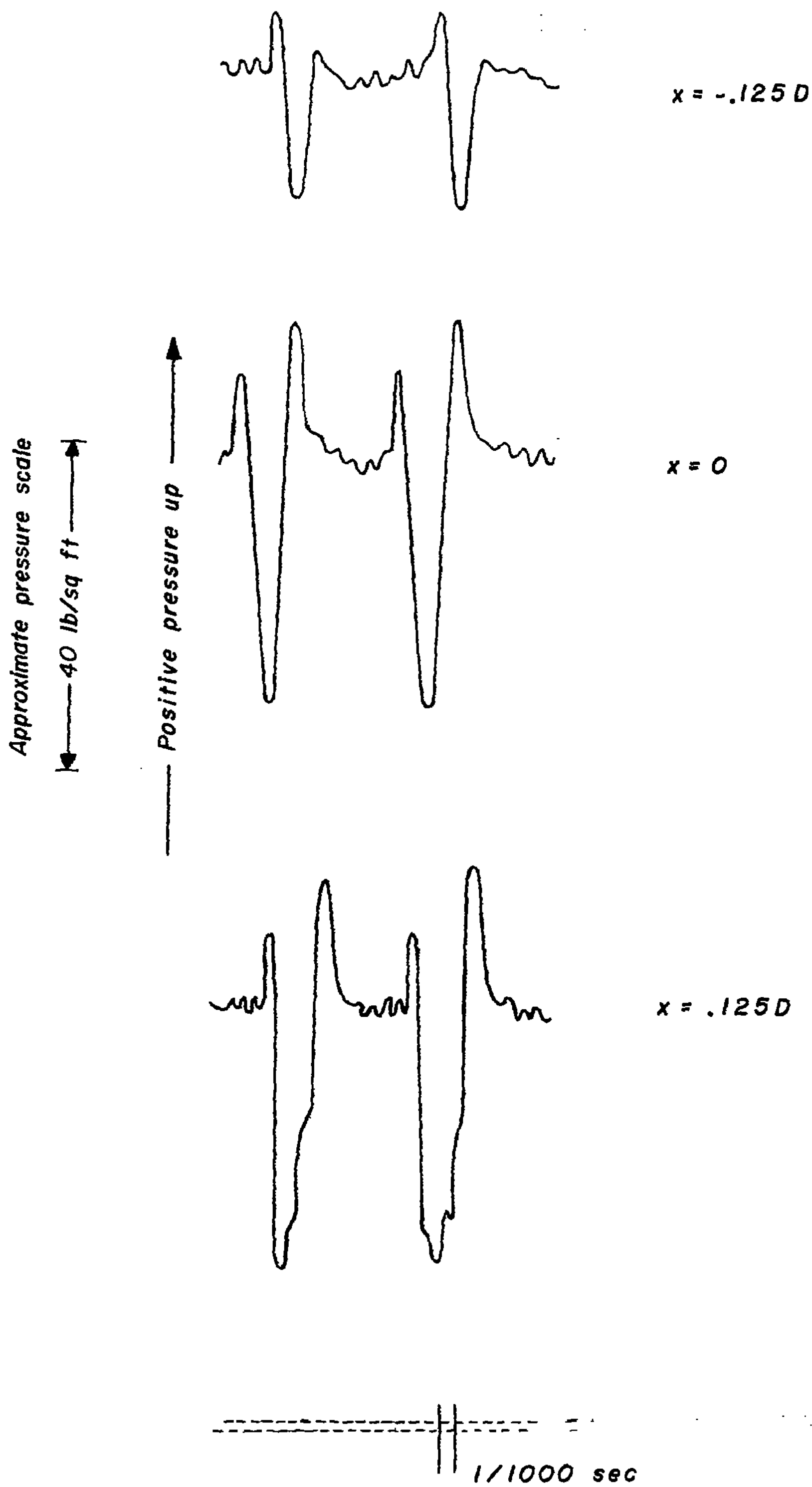

Figure 14.- Variation of wave form of propeller noise with axial microphone location. $M_o \approx 0.71$; $M_t \approx 1.05$; $N \approx 2{,}900$ rpm; $y = 0.655D$.